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CHARM HADRONIC DECAYS FROM FOCUS: LESSONS LEARNT

STEFANO BIANCO*

*Laboratori Nazionali di Frascati dell'INFN, v. E. Fermi 40
 Frascati, 00044 Italy
 stefano.bianco@lnf.infn.it*

DANIELE PEDRINI

*INFN Milano Bicocca, Edificio U2 - Piazza della Scienza 3
 I-20126 Milano - Italy
 daniele.pedrini@mib.infn.it*

ALBERTO REIS

*Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud, 150 - Urca
 Rio de Janeiro - RJ - Brasil 22290-180
 alberto@cbpf.br*

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The FOCUS photoproduction experiment took data in the nineties and produced a wealth of results in charm physics. Some of the studies were seminal for contemporary experiments, and even paved the way for the technology of many charm and beauty analysis tools.

Keywords: charm; hadronic decays; Photoproduction.

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1. Introduction

A retrospective discussion of selected FOCUS hadronic decays results which have interest and implications for ongoing and future studies in charm and beauty decays is presented. Topics which had long lasting effects on heavy flavour physics are discussed, such as the measurement of y_{CP} parameter in D mixing, the study of T-odd correlations, and the four-body amplitude analysis.

Data were collected 1996-1997 with the FOCUS spectrometer at the Fermilab Tevatron Wide Band photon beam. The FOCUS spectrometer¹ was successor to E687 and designed to study charm particles produced by 200 GeV photons using a fixed target spectrometer with vertexing, cerenkov detectors, em calorimeters, and

*Presenter

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muon id capabilities. Member groups of the FOCUS collaboration were from USA, Italy, Brazil, Mexico, Korea.

2. The y_{CP} parameter

The study ² consisted of a comparison of the lifetime of a CP even final state, $D^0 \rightarrow K^- K^+$, to the lifetime of a CP mixed decay, $D^0 \rightarrow K^- \pi^+$. The lifetime measurements (Fig. 1) were made using high signal-to-background D^0 samples consisting of 10 331 decays into $K^- K^+$, and 119 738 decays into $K^- \pi^+$. The measurement of lifetime differences corresponded to a direct measurement of the mixing parameter $y_{CP} = (\Gamma(\text{CP even}) - \Gamma(\text{CP odd})) / (\Gamma(\text{CP even}) + \Gamma(\text{CP odd})) = 0.0342 \pm 0.0139 \pm 0.0074$.

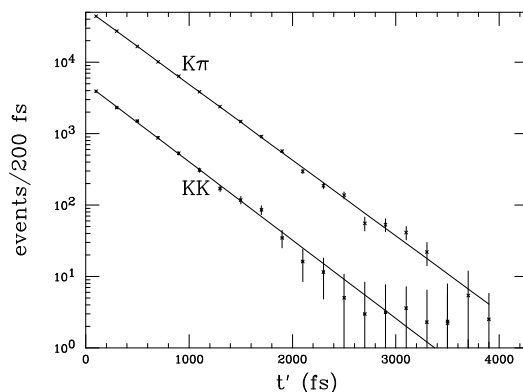
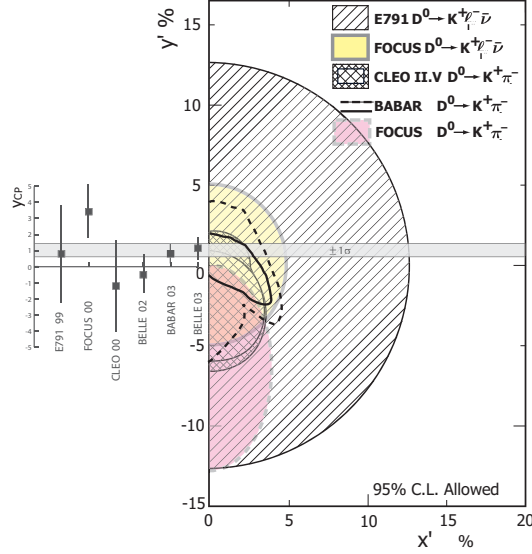


Fig. 1. Signal versus reduced proper time for $D^0 \rightarrow K^- \pi^+$ and $K^- K^+$ requiring $W_\pi - W_K > 4$ and $\ell/\sigma > 5$. The fit is over 20 bins of 200 fs bin width. The data is background subtracted and includes the (very small) Monte Carlo correction.

Such a first evidence for nonzero mixing was followed by higher-statistics measurements from B-factories. Fig.2 from a 2003 review paper ³ shows the FOCUS measurement compared to the existing studies. With a moderate significance due to low statistics, FOCUS showed evidence for a nonzero lifetime difference. Recent results from BABAR and BELLE have solidly established the observation of D mixing. Algorithms and selections used by FOCUS may be used by forward-geometry experiment LHCb at the CERN LHC with much larger statistics very soon.

3. T-odd correlations

Triple-product correlations of the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each \vec{v}_i is a spin or momentum, are odd under time reversal (T). By the CPT theorem, a nonzero value for these correlations would also be a signal of CP violation. A nonzero triple-

Fig. 2. Summary of x', y', y_{CP} measurements in 2003.

product correlation is evidenced by a nonzero value of the asymmetry

$$A_T \equiv \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)} \quad (1)$$

where Γ is the decay rate for the process. There is a well-known technical complication: strong phases can produce a nonzero value of A_T , even if the weak phases are zero, that is CP and T violation are not necessarily present. Thus, strictly speaking, the asymmetry A_T is not in fact a T -violating effect. Nevertheless, one can still obtain a true T -violating signal which takes care of the complications due to strong phases by measuring a nonzero value of

$$A_{T\text{viol}} \equiv \frac{1}{2}(A_T - \overline{A_T}) \quad (2)$$

where $\overline{A_T}$ is the T -odd asymmetry measured in the CP -conjugate decay process. This study was inspired by a paper of Ikaros Bigi⁵. In his paper Bigi suggested a search for T violation by looking at the triple-product correlation (using the momenta of the final state particles) in the decay mode $D^0 \rightarrow K^- K^+ \pi^- \pi^+$. Such a correlation must necessarily involve at least four final-state particles. This can be understood by considering the rest frame of the decaying particle and invoking momentum conservation. The number of independent three-momenta is one less than the number of final-state particles, so a triple product composed entirely of momenta requires four particles in the final state. We calculate $A_{T\text{viol}}$ for the decay modes $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ and $D_{(s)}^+ \rightarrow K_S^0 K^+ \pi^- \pi^+$ using data from the FOCUS experiment, finding, with about 800 D^0 events⁴, $A_{T\text{viol}}(D^0) = 0.010 \pm 0.057(\text{stat.}) \pm$

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0.037(syst.), and, with about 500 D^+ and 500 D_s^+ events, $A_{\text{Tviol}}(D^+) = 0.023 \pm 0.062(\text{stat.}) \pm 0.022(\text{syst.})$, and $A_{\text{Tviol}}(D_s^+) = -0.036 \pm 0.067(\text{stat.}) \pm 0.023(\text{syst.})$.

In 2010 BABAR published new limits⁶ by using the same FOCUS formalism. With $4.7 \cdot 10^4$ events, BABAR measured $A_{\text{Tviol}}(D^+) = 0.0010 \pm 0.0051(\text{stat.}) \pm 0.0044(\text{syst.})$. Another order of magnitude limit reduction is expected with the Frascati and KEK super-b factories data samples. For an updated discussion see⁷.

4. Four-body amplitude analysis

FOCUS published the first study^{8,9,10} with a complete 4-body formalism of $\text{KK}\pi\pi$, $\text{KKK}\pi$, $\pi\pi\pi\pi$. In this conference report only the $\pi\pi\pi\pi$ channel is discussed, with 6.3k events. This decay has a direct connection to decays used for extraction of CKM parameters in B decays such as the angle α from $B \rightarrow \rho^0 \rho^0$.

A simple isobar model was used with a total of nine amplitudes and 16 free parameters: $D \rightarrow \rho^0 \rho^0$; $D \rightarrow a_1 \pi, a_1 \rightarrow \rho^0 \pi$; $D \rightarrow R \pi \pi, R \equiv (\sigma, \rho^0, f_0(980), F_2(1270))$. As customary in all isobar models, final state interactions (FSI) are not fully accounted for. Several helicity states were considered in the fit functions. The study showed how the dominant contribution to the $\pi\pi\pi\pi$ state comes from the $a_1^+(1260)\pi^-$ mode, which accounts for over 60% of the total decay rate. The remaining part of the decay rate is equally divided between $\rho^0 \rho^0$ and the quasi-three-body modes $D \rightarrow R \pi \pi$. The scalar component is dominated by the decay $D^0 \rightarrow \sigma \pi \pi$. The fit get significantly worse if the $\sigma \pi \pi$ amplitude is replaced by an uniform non-resonant component.

Most important, although the one-dimensional projections suggest a good fit, the goodness-of-fit tested on the full 5-dimensional phase space is poor. This indicates that other effects need to be taken into account for a more realistic model. One important ingredient is the final state interaction (FSI), which could introduce energy-dependent phases. One needs to build a model for the FSI based on chiral perturbation theory, but this is rather challenging even for three-body final states. Another effect that could play a role is the Bose-Einstein correlation between the two pairs of identical pions.

The final message is that, at least in four-body decays, the strong interaction phases are still not under control, which makes the extraction of weak phases governing CP violation rather uncertain.

5. Epilogue: on the importance of Dalitz analysis in the extraction of CKM parameters

Dalitz plot analysis is fundamental for a meaningful investigation of decay modes in which resonances are present. As an example, FOCUS showed¹¹ in the analysis of the decay mode $D^0 \rightarrow K_s K^+ K^-$ that a contamination from $f_0(980)$ under the $\phi(1020)$ signal is always present if a simple mass cut is applied. This, however, changes the assignment of the final state, since $K_s \phi$ is a CP-odd state, while $K_s f_0$ is CP-even.

These considerations forced, in early 2000s, the B-factory experiments to revisit their analyses of some decay modes such as $B^0 \rightarrow K_s K^- K^+$. Nowadays these analyses are performed with the Dalitz plot technique.

6. Conclusions

FOCUS/E687 was a pioneering expedition towards the charm unexplored territories, the first experiment which had important measurements for all weakly decaying charm hadrons including weak lifetimes up to the Ω_c , thus showing us that some non-perturbative QCD effects could be understood. FOCUS gave hints of unexpected phenomena such as a positive value for the y_{CP} parameter in charm mixing, which is still today debated subject of studies, and possibly the only mixing parameter significantly different from zero observed so far. FOCUS did pioneering work for three-body final states to help us in the future to find CPV in D decays, and to help understand CP searches in B decays. Future searches for CPV from New Physics need much more experimental and theoretical work. Finally, FOCUS did pioneering work in $D \rightarrow 4h$, useful for the future and showing that more theoretical work is needed. From the experimental side, while BaBar/BELLE reached the 1% level in CPV limits, much more statistics is needed to reach the 0.1% level where NP can generate effects.

Three FOCUS hadronic decays results have been singled out and discussed. The results have implications on upcoming new results from the contemporary charm and beauty experiments. Algorithm and selection used by FOCUS in the study of y_{CP} parameter in D mixing may be used by forward-geometry experiment LHCb with much larger statistics. The formalism for the search of CP violation via T-odd correlations was developed, and first limit on KK final state published, which was followed in 2010 by the new limit from BABAR in 2010 using the same formalism. The first study with a complete 4-body formalism of $KK\pi\pi$, $KKK\pi$, $\pi\pi\pi\pi$ provided a direct connection to decays used for extraction of CKM angle α in B decays: the poor 5D fit quality which emerges in high-statistics studies implies the need for a better understanding of nonresonant component. Finally, Dalitz plot analyses from FOCUS showed the importance of studying the resonant structure of hadronic decays: S-waves cannot be taken out with a simple mass cut.

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References

1. P. L. Frabetti *et al.* [E-687 Collaboration], Nucl. Instrum. Meth. A **320**, 519 (1992).
2. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **485**, 62 (2000) [arXiv:hep-ex/0004034].

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3. S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7**, 1 (2003) [arXiv:hep-ex/0309021].
4. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **622**, 239 (2005) [arXiv:hep-ex/0506012].
5. I.I. Bigi, in Proceedings of KAON2001: International Conference on *CP* Violation, Pisa, Italy, 12-17 Jun 2001, p.417 (hep-ph/0107102).
6. P. del Amo Sanchez *et al.* [The BABAR Collaboration], Phys. Rev. D **81**, 111103 (2010) [arXiv:1003.3397 [hep-ex]].
7. D. Pedrini, in The Heavy Flavor Averaging Group (D. Asner *et al.*), arXiv:1010.1589v1.
8. J. M. Link *et al.* [FOCUS Collaboration], Phys. Rev. D **75**, 052003 (2007) [arXiv:hep-ex/0701001].
9. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **610**, 225 (2005) [arXiv:hep-ex/0411031].
10. J. M. Link *et al.* [FOCUS Collaboration], Phys. Lett. B **575**, 190 (2003) [arXiv:hep-ex/0308054].
11. This argument was first pointed out by D. Pedrini, D. Pedrini, *Presented at 1st International Workshop on Frontier Science: Charm, Beauty, and CP, Frascati, Rome, Italy, 6-11 Oct 2002.*

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Displayed equations should be numbered consecutively in each section, with the number set flush right and enclosed in parentheses

$$\mu(n, t) = \frac{\sum_{i=1}^{\infty} 1(d_i < t, N(d_i) = n)}{\int_{\sigma=0}^t 1(N(\sigma) = n) d\sigma}. \quad (1)$$

Equations should be referred to in abbreviated form, e.g. “Eq. (1)” or “(2).” In multiple-line equations, the number should be given on the last line.

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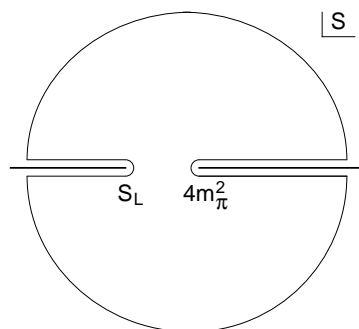


Fig. 1. A schematic illustration of dissociative recombination. The direct mechanism, $4m_\pi^2$ is initiated when the molecular ion S_L captures an electron with kinetic energy.

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Fig. 1) and typeset in 8 pt roman with baselineskip of 10 pt. Use double spacing between a caption and the text that follows immediately.

Figures should be black and white (or half-tone) and of a good resolution and sharpness. Compressed formats, such as JPEG, should not use heavy compression, which introduces undesirable artifacts. Bitmap figures, such as photographs or half-tone images, should be at least 300 dpi (TIFF, BMP or JPEG). Vector (line-art) figures, such as charts and technical drawings, should be 600–1200 dpi (EPS, PS, PDF). The native formats of software packages will not be permitted.

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Table 1. Comparison of acoustic for frequencies for piston-cylinder problem.

Piston mass	Analytical frequency (Rad/s)	TRIA6- S_1 model (Rad/s)	% Error
1.0	281.0	280.81	0.07
0.1	876.0	875.74	0.03
0.01	2441.0	2441.0	0.0
0.001	4130.0	4129.3	0.16

If tables need to extend over to a second page, the continuation of the table should be preceded by a caption, e.g. “*Table 2. (Continued)*”.

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Acknowledgments

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Appendices should be used only when absolutely necessary. They should come before the References. If there is more than one appendix, number them alphabetically. Number displayed equations occurring in the Appendix in this way, e.g. (A.1), (A.2), etc.

$$g_{\mu_1\mu_2} = g_{axy} = -\epsilon_{abc}4\pi \frac{(x-y)^c}{|x-y|^3}, \quad (\text{A.1})$$

$$h_{\mu_1\mu_2\mu_3} = \epsilon^{\alpha_1\alpha_2\alpha_3} g_{\mu_1\alpha_1} g_{\mu_2\alpha_2} g_{\mu_3\alpha_3}$$

with

$$\epsilon^{\alpha_1\alpha_2\alpha_3} = \epsilon^{b_1y_1b_2y_2cx} = \epsilon^{b_1b_2c} \delta(x-y_1) \delta(x-y_2). \quad (\text{A.2})$$

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References

1. R. Loren and D. B. Benson, *J. Comput. System Sci.* **27**, 400 (1983).
2. OPAL Collab. (G. Abbiendi *et al.*), *Eur. J. Phys. C* **11**, 217 (1999).
3. R. Loren and D. B. Benson, *Introduction to String Field Theory*, 2nd edn. (Springer-Verlag, New York, 1999).
4. R. Loren and D. B. Benson (eds.), *Introduction to String Field Theory*, 2nd edn. (Springer-Verlag, New York, 1999).
5. C. M. Wang, J. N. Reddy and K. H. Lee, New set of buckling parameters, in *Shear Deformable Beams*, ed. T. Rex (Elsevier, Oxford, 2000), p. 201.
6. R. Loren, J. Li and D. B. Benson, Deterministic flow-chart interpretations, in *Introduction to String Field Theory*, Ad. Series in Math. Phys., Vol. 3 (Springer-Verlag, New York, 1999), p. 401.
7. R. Loren, J. Li and D. B. Benson, Deterministic flow-chart interpretations, in *Proc. 3rd Int. Conf. Entity-Relationship Approach*, eds. C. G. Davis and R. T. Yeh (North-Holland, Amsterdam, 1983), p. 421.
8. R. Loren, J. Li and D. B. Benson, Deterministic flow-chart interpretations, to appear in *J. Comput. System Sci.*